

Quantitative evaluation of ionosphere models for reproducing regional TEC during geomagnetic storms

Ja Soon Shim^{1*}, Maria M Kuznetsova², Lutz Rastaetter², Dieter Bilitza³, Mihail Codrescu⁴, Anthea J Coster⁵, Barbara A Emery⁶, Mariangel Fedrizzi⁴, Ben T Foster⁶, Timothy J Fuller-Rowell⁴, Joe Huba⁷, Larisa Goncharenko⁵, Aaron J Ridley⁸, Ludger Scherliess⁹, Robert W. Schunk⁹, Jan J. Sojka⁹, Lie Zhu⁹

1. CUA/NASA GSFC, Greenbelt, MD, USA, 2. NASA/GSFC, Greenbelt, MD, USA, 3. School of Physics Astronomy and Computational Science, George Mason University, Fairfax, Virginia, USA, 4. NOAA SWPC, Boulder, CO, USA, 5. Haystack Observatory, Westford, MA, USA, 6. NCAR HAO, Boulder, CO, USA, 7. Plasma Physics Division, Naval Research Laboratory, Washington, D. C., USA, 8. Space Physics Research Laboratory, Univ. of Michigan, Ann Arbor, MI, USA, 9. Utah State Univ. Logan, UT, USA

<http://ccmc.gsfc.nasa.gov>

NASA Goddard Space Flight Center



Abstract

TEC (Total Electron Content) is one of the key parameters in description of the ionospheric variability that has influence on the accuracy of navigation and communication systems. **To assess current TEC modeling capability** of ionospheric models during geomagnetic storms and to establish a baseline against which future improvement can be compared, we quantified the ionospheric models' performance by **comparing modeled vertical TEC values with ground-based GPS TEC measurements. The comparison focused on North America sector during selected two storm events: 2006 AGU storm (14-15 Dec. 2006) and 2013 March storm (17-19 Mar. 2013).** The ionospheric models used for this study range from empirical to physics-based, and physics-based data assimilation models. We investigated the TEC variations during the storms. In this presentation, we focus on preliminary results of the comparison of the models performance in reproducing the storm-time TEC variations **using RMS error** and several parameters such as **maximum change** during the storms. In addition, we studied the **sensitivity of TEC to $O^+ - O$ collision frequency (Burnside factor) and F10.7** using CTIPe. This study has been supported by the Community Coordinated Modeling Center (CCMC) at the Goddard Space Flight Center. Model outputs and observational data used for the study will be permanently posted at the CCMC website (<http://ccmc.gsfc.nasa.gov>) for the space science communities to use.

Setup

- Time interval:
 - **200612 event:** 2006/12/13 (doy 347) - 12/16 (doy 350) (Dst_min = -162 nT)
 - **201303 event:** 2013/03/16 (doy 75)– 03/20 (doy 79) (Dst_min = -132 nT)
- 7 IT models: IRI2012, IFM, SAMI3, CTIPE, GITM, TIEGCM, and USU- GAIM
- Observation:
 - GPS vertical TEC
 - North America Sector (240°E - 300°E, 0°N-90°N)
 - 2.5° lat x 5.0° lon x 5 min
- Compared the model performance for three latitude regions (low: lat < 25°N, middle: 25°N < lat < 50°N , and high: lat > 50°N) using
 - RMS error
 - Max_s (max. during storm time) – Max_q (max. during quiet time)
 - Min_s (min. during storm time) – Min_q (min. during quiet time)
 - (Max-Min)_s– (Max-Min)_q

Model Simulations & Measurement used for the study

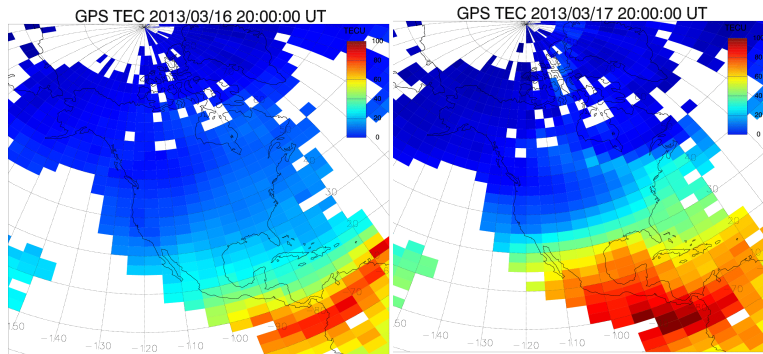
Model Setting ID	
empirical model	
IRI	IRI-2012 using IRI-corr for topside Ne and CCIR F-peak
physics-based ionosphere model	
SAMI3	SAMI3 with the neutral wind model HWM93
IFM	IFM driven by F10.7, Kp and empirical inputs for the thermosphere parameters
physics-based coupled ionosphere-thermosphere model	
CTIPE	CTIPE driven by Weimer electric potential model, $2^\circ \times 18^\circ$, 15 levels in logarithm of pressure
TIE-GCM	TIE-GCM1.95 driven by Weimer electric potential model
GITM	GITM 2.0 driven by Weimer electric potential model
physics-based data assimilation ionosphere model	
1_USU-GAIM	USU-GAIM23 with GPS TEC observations from up to 400 ground stations
Measurements Setting ID	
MIT GPS TEC	Vertical GPS TEC data, 2.5° lat x 5.0° lon x 5 min provided by MIT

*All runs are performed at the CCMC

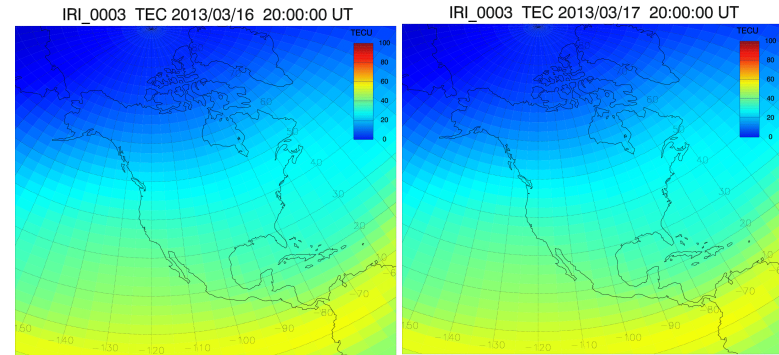
Modeled TEC & Observed vTEC (201303 event):

before storm onset (03/16 20:00 UT) and during main phase (03/17 20:00 UT)

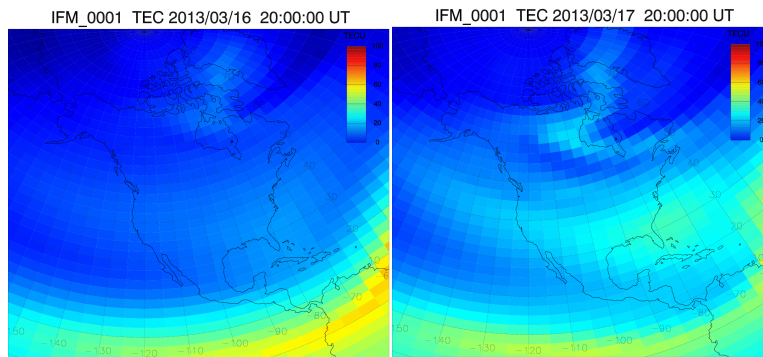
GPS TEC



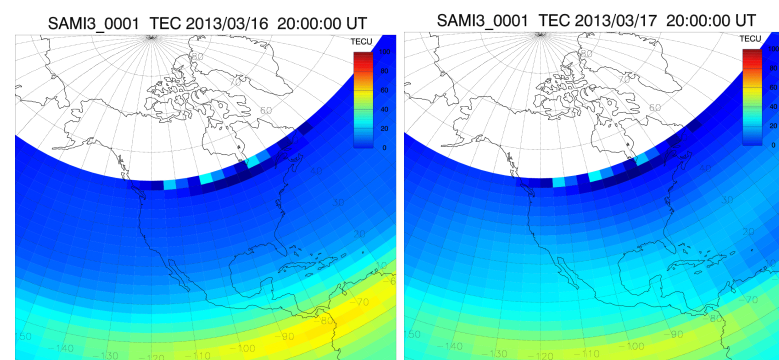
IRI2012



IFM

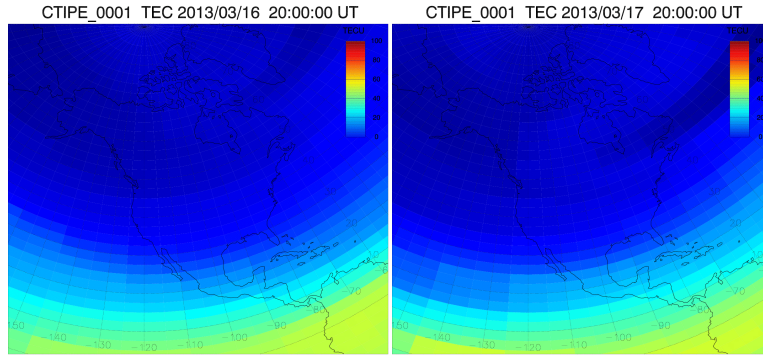


SAMI3

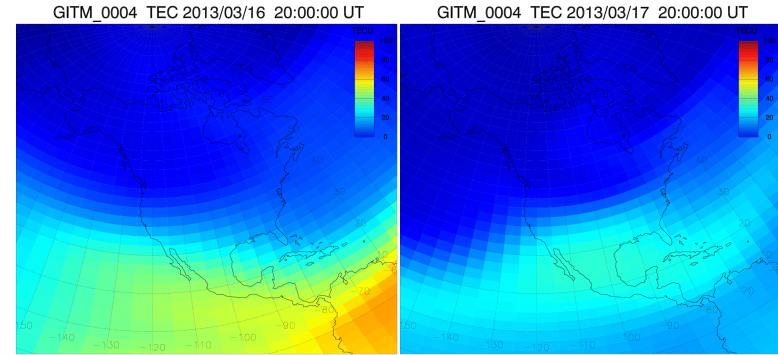


- GPS vTEC shows TEC enhancement in low and middle latitudes and slight decrease in high latitude region during the 2013 Mar. storm.
- Empirical model, IRI, hardly shows the changes in TEC.
- Physics based ionospheric models:
 - IFM produces TEC changes better than SAMI3 does.

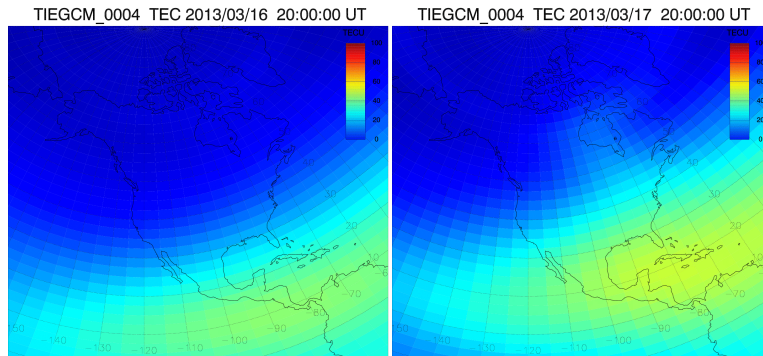
CTIPE



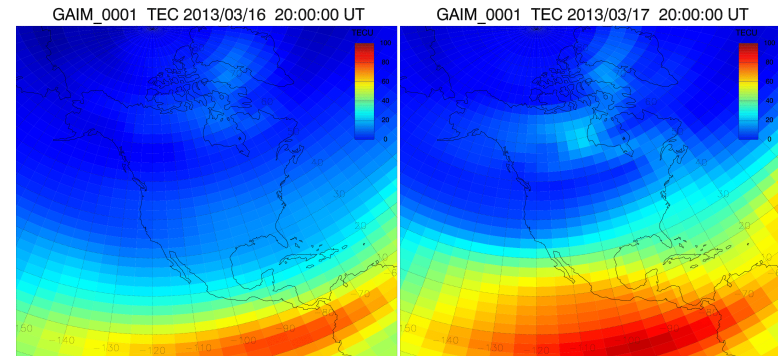
GITM



TIE-GCM



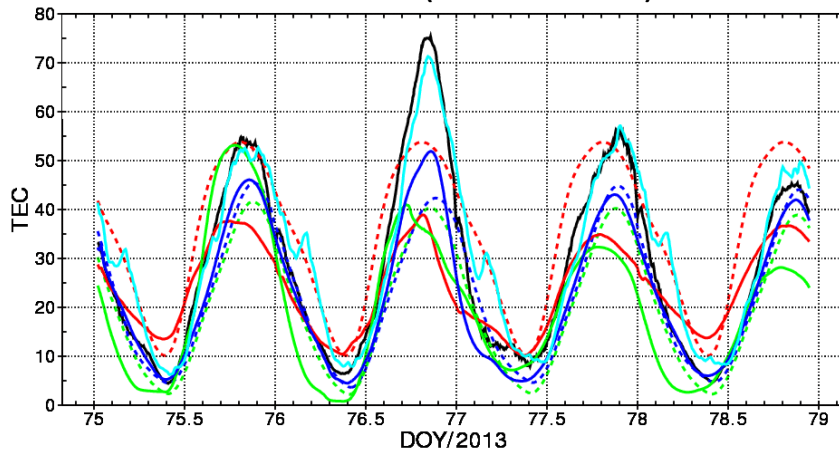
USU-GAIM



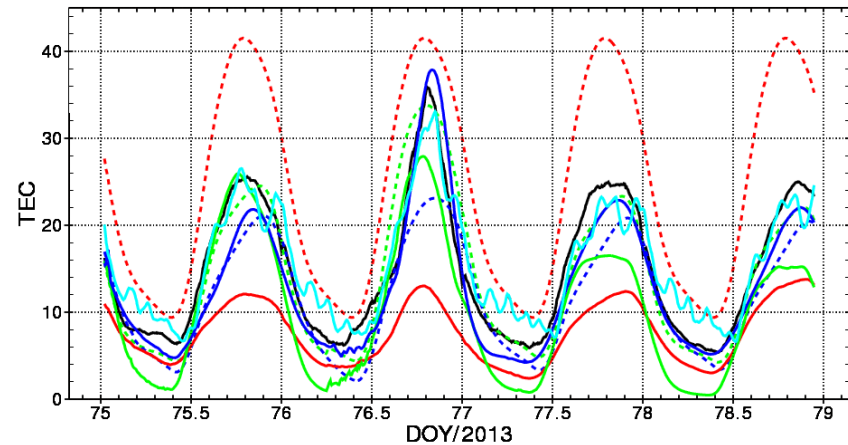
- Physics based coupled models:
 - CTIPE hardly shows the changes in TEC during the storm.
 - TIE-GCM produces TEC increase in low latitudes, while GITM produces TEC decrease during the storm.
- Data assimilation model, USU-GAIM, shows better agreement with the observed GPS vTEC in low latitude region than other model simulations do.

Average TEC at three latitude regions (201303)

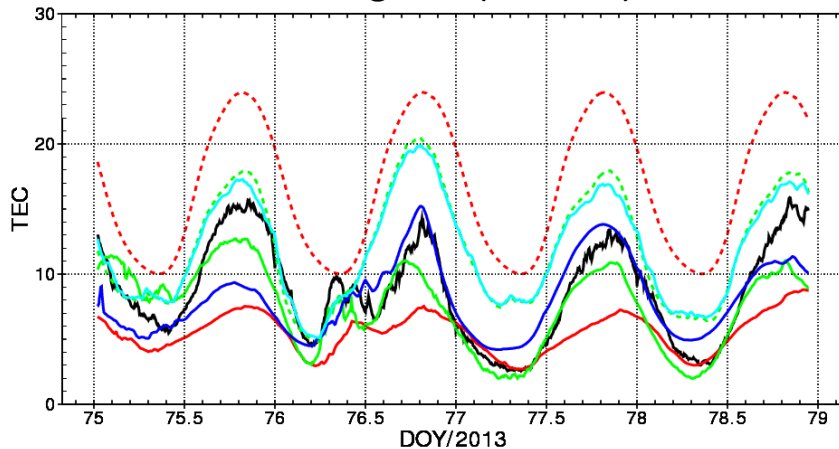
low lat ($0^\circ < \text{lat} < 25^\circ$)



middle lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($50^\circ < \text{lat}$)



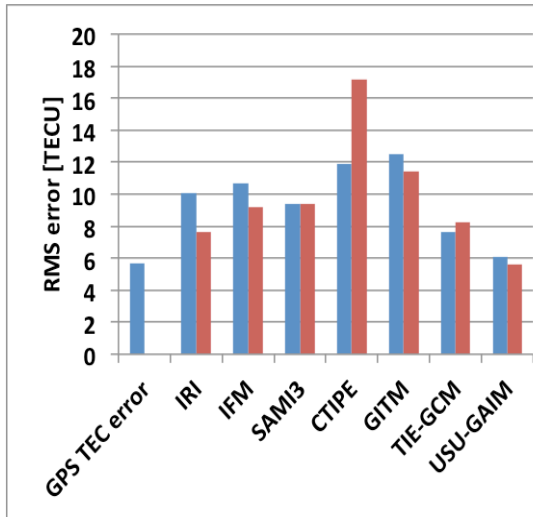
- During 2013 March storm, daytime latitudinal average TEC increases by about 20 TECU in low and 10 TECU in middle latitudes, while the average TEC slight decreases in high latitude region.

— MIT GPS VTEC
 - - - IRI
 - - - IFM
 - - - SAMI3
 — CTIPE
 — GITM
 — TIE-GCM
 — USU-GAIM

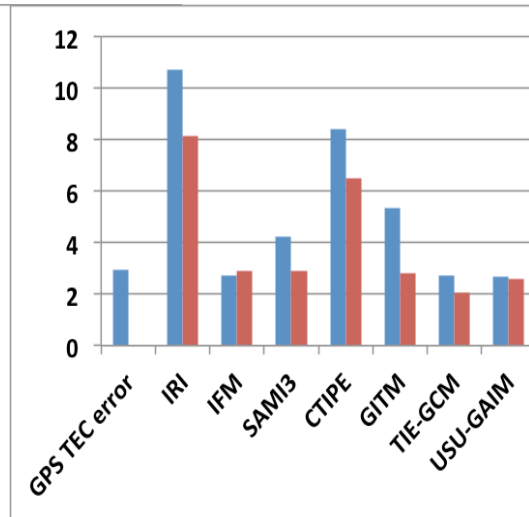
- USU-GAIM and TIE-GCM show better agreement with GPS TEC in middle latitude regions.
- CTIPE and GITM tend to underestimate daytime TEC, however they well produce increase in night time TEC during the storm (doy 76 about 07:00 UT)

RMS error in predicting TEC over North America (201303)

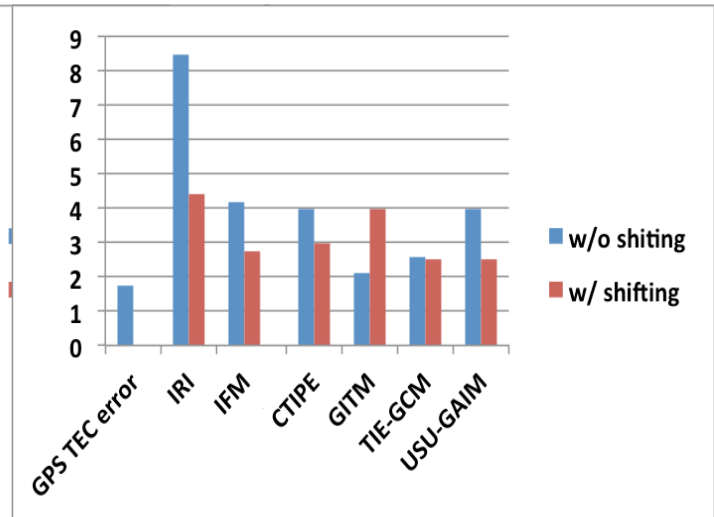
low lat ($0^\circ < \text{lat} < 25^\circ$)



mid-lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($\text{lat} > 50^\circ$)



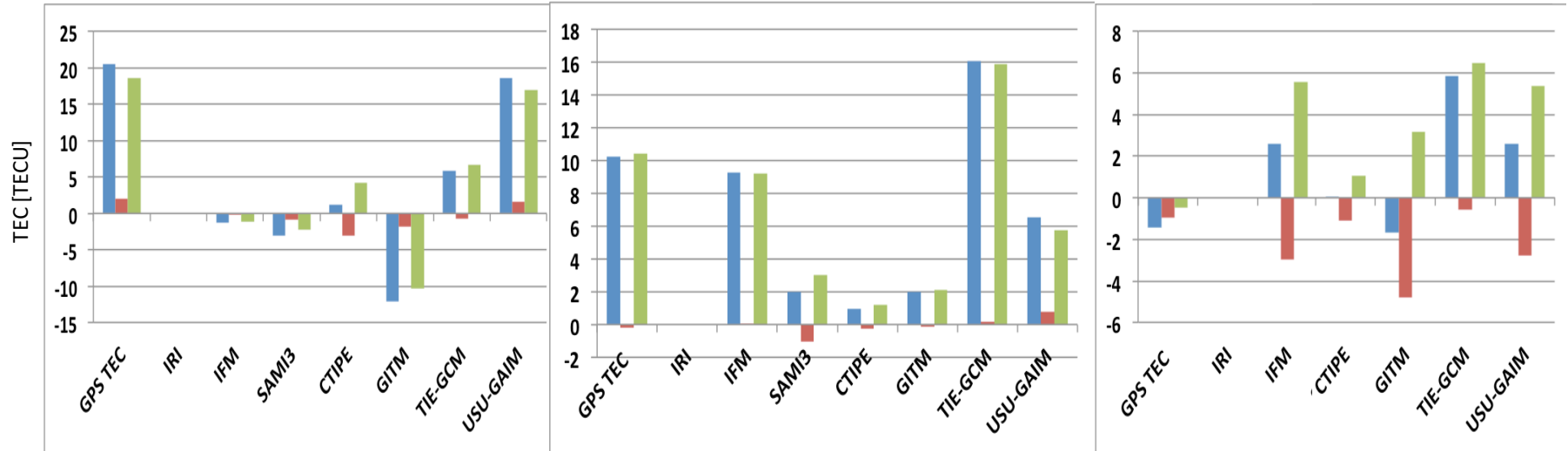
- Red bar: RMS errors of shifted TEC; TEC – pre-storm TEC_{min} (quiet day: 03/16)
- GPS TEC error: average error of vertical TEC over the latitude regions
- Most models' RMS error are larger than GPS TEC error in low and high latitude regions, while most physics based models' RMS error of shifted TEC are smaller than GPS TEC error in middle latitudes.
- RMS error of shifted TEC of IFM and SAMI3 are similar each other.
- USU-GAIM produces the better TEC than others for most cases.
- TIE-GCM shows the best score with shifting in middle latitudes, while GITM shows the best score without shifting in high latitudes.
- Physics based models' performance in predicting TEC in high latitude is comparable to that of USU-GAIM.
- IRI RMS error is reduced after shifting TEC.

Maximum Change in TEC during 201303 storm event

low lat ($0^\circ < \text{lat} < 25^\circ$)

mid-lat ($25^\circ < \text{lat} < 50^\circ$)

high lat ($\text{lat} > 50^\circ$)



■ **max_s - max_q** = max. of latitudinal average TEC on 03/17 – max. of latitudinal average TEC on 03/16

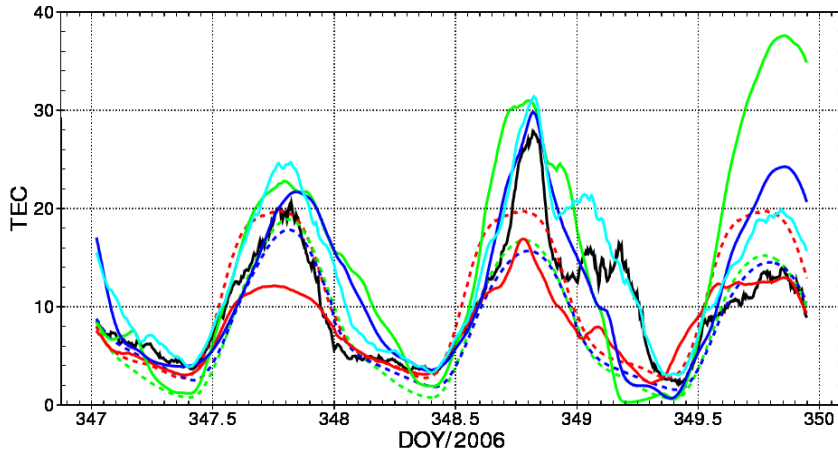
■ **min_s - min_q** = min. of latitudinal average TEC on 03/17 – min. of latitudinal average TEC on 03/16

■ **(max-min)_s - (max-min)_q**

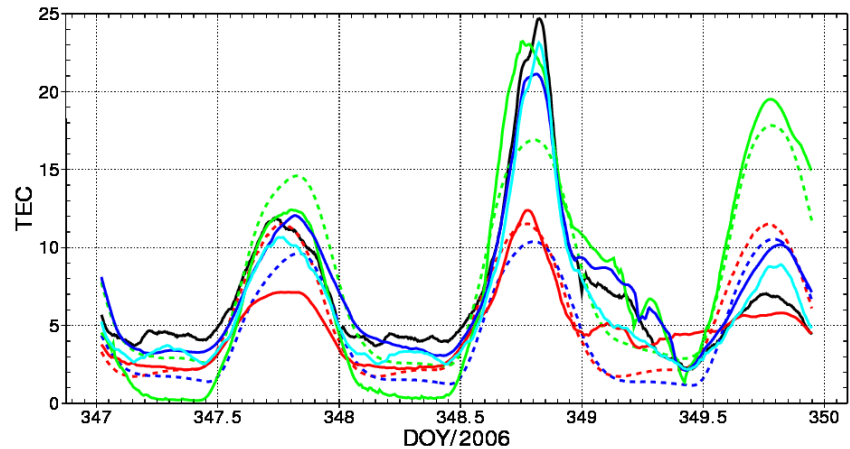
- During the 2013 Mar. storm, both daytime TEC max. and nighttime TEC min. increase in low latitudes, while those decrease in high latitudes.
- Most models underestimate TEC increase during the storm in low and middle latitudes, and overestimate TEC in high latitudes.
- USU-GAIM and IFM predict better change in TEC than others in low and middle latitudes respectively.
- GITM shows the best agreement of max_s-max_q with the measured value in high latitudes.
- Empirical model IRI does not show changes in TEC max. value.
- In low latitudes, changes in max. of TEC of IFM, SAMI3 and GITM are negative, while others produce positive values.

Average TEC at three latitude regions (200612)

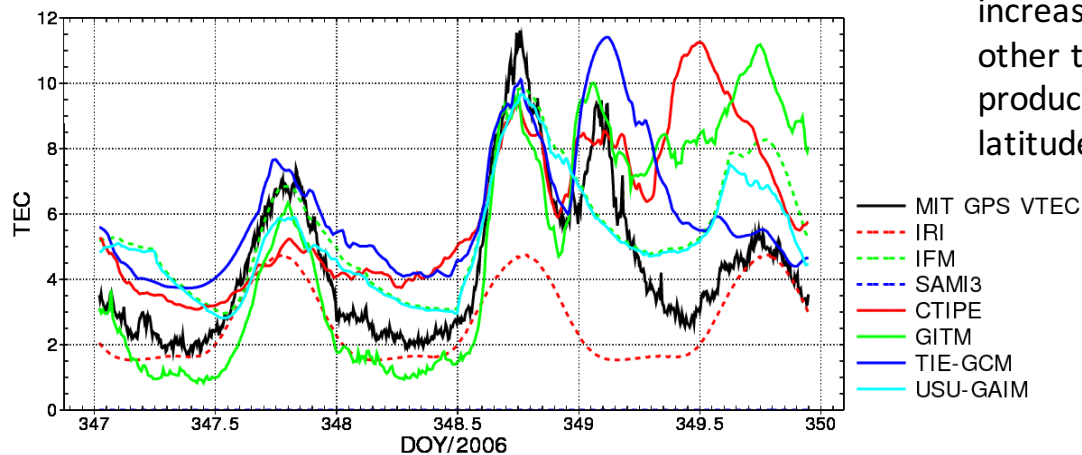
low lat ($0^\circ < \text{lat} < 25^\circ$)



middle lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($50^\circ < \text{lat}$)



- During 2006 Dec. storm, daytime latitudinal average TEC increases in all three latitude regions, the increase in middle latitude is larger than that in other two latitude regions, while 2013 Mar. storm produces the largest daytime TEC change in low latitudes.

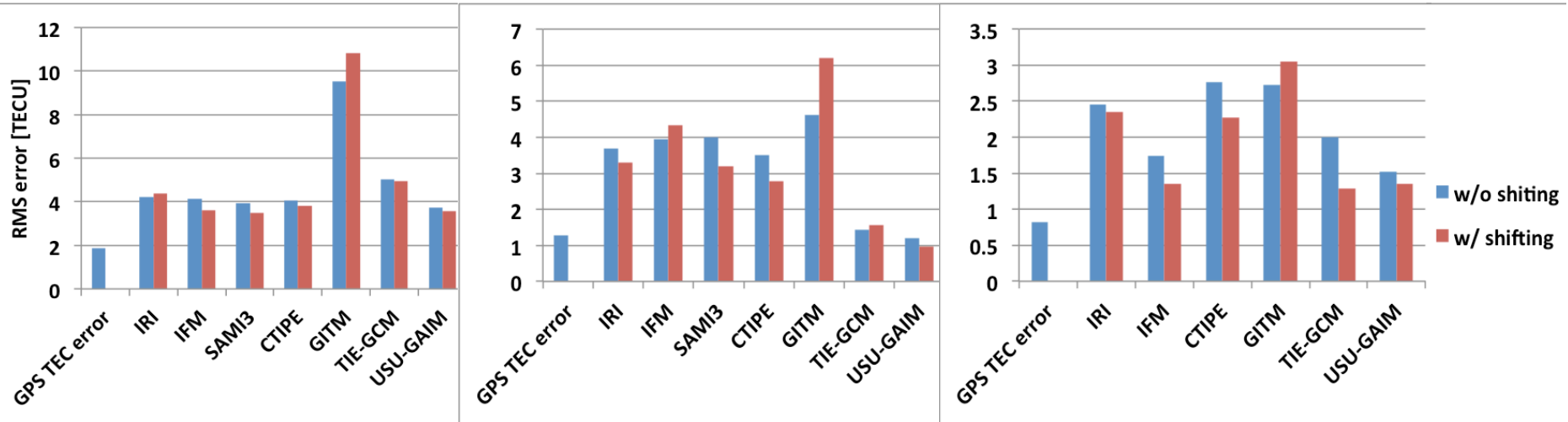
- Most models underestimate TEC during storm main phase in middle latitude, and overestimate during recovery phase.
- Physics based coupled models produce TEC increase around 3:00 UT on day 349 better than USU-GAIM.

RMS error in predicting TEC over North America (200612)

low lat ($0^\circ < \text{lat} < 25^\circ$)

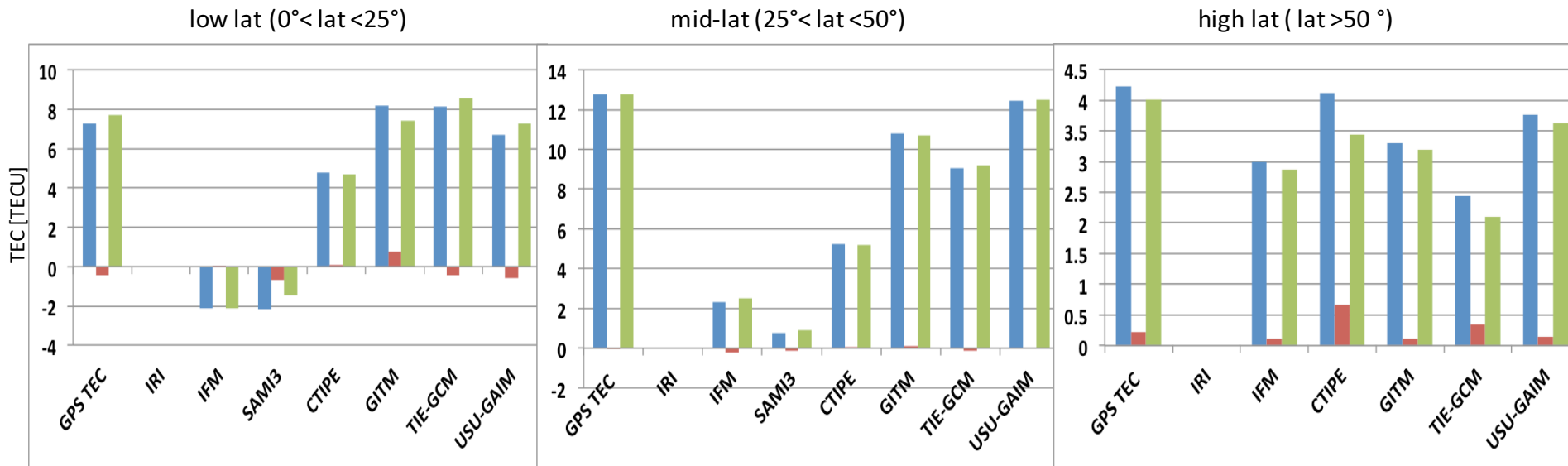
mid-lat ($25^\circ < \text{lat} < 50^\circ$)

high lat ($\text{lat} > 50^\circ$)



- Red bar: RMS errors of shifted TEC; TEC – pre-storm TEC_{min} (quiet day: 12/13)
- GPS TEC error: average error of vertical TEC over the latitude regions.
- Most cases, the models show better score with shifting except for GITM.
- All models' RMS error are larger than GPS TEC error in all three low latitude latitude regions except for USU-GAIM RMS error in middle latitudes.
- USU-GAIM produces the better TEC than others for most cases.
- SAMI3 shows the best score with shifting in low latitudes, while TIE-GCM shows the best score with shifting in high latitudes.

Maximum Change in TEC during 200612 storm event

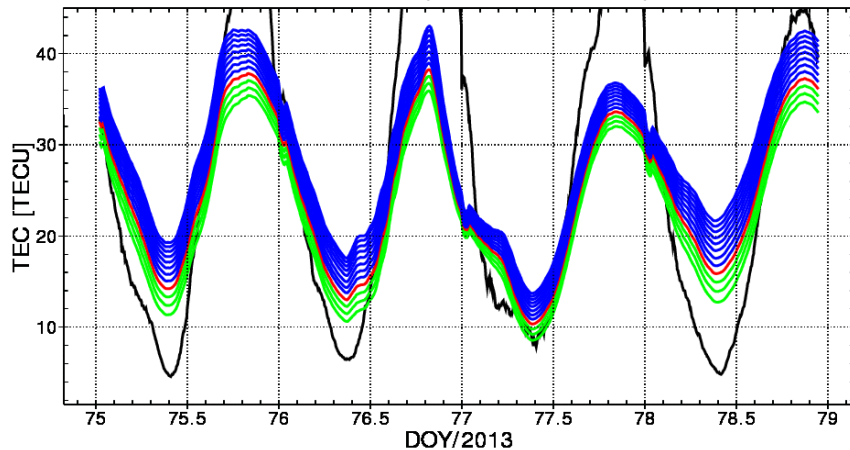


- $\max_s - \max_q$ = max. latitudinal average TEC on 12/14 – max. latitudinal average TEC on 12/13
- $\min_s - \min_q$ = min. latitudinal average TEC on 12/14 – min. latitudinal average TEC on 12/13
- $(\max - \min)_s - (\max - \min)_q$

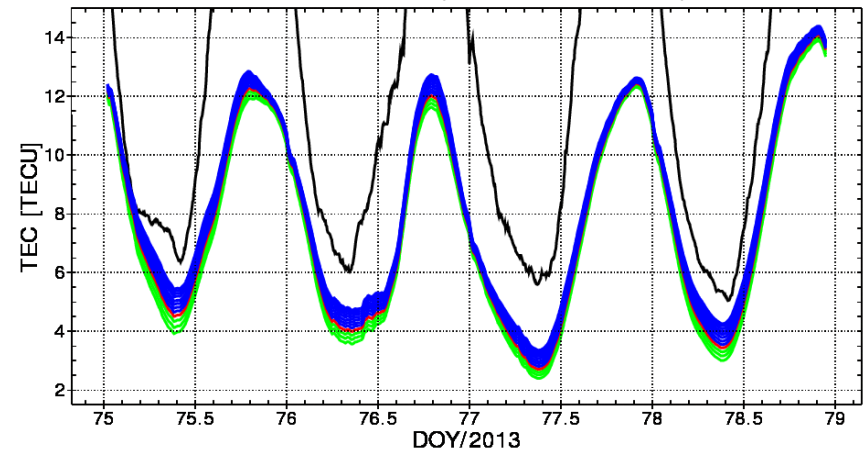
- Physics based coupled models show better TEC changes during the 2006 Dec. than the ionosphere models.
- USU-GAIM produces the best max. change in average TEC than middle latitudes.
- CTIPE shows the best agreement of $\max_s - \max_q$ with the measured value in high latitudes.
- Empirical model IRI does not show changes in average TEC maximum.
- In low latitudes, changes in max. of TEC of IFM and SAMI3 are negative, while others produce positive values as same as 2013 Mar. storm event.

Sensitivity of TEC to Burnside Factor (201303)

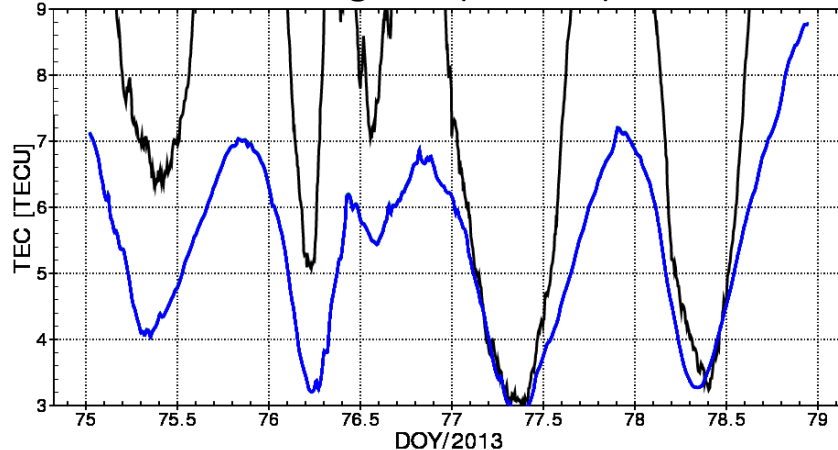
low lat ($0^\circ < \text{lat} < 25^\circ$)



middle lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($50^\circ < \text{lat}$)



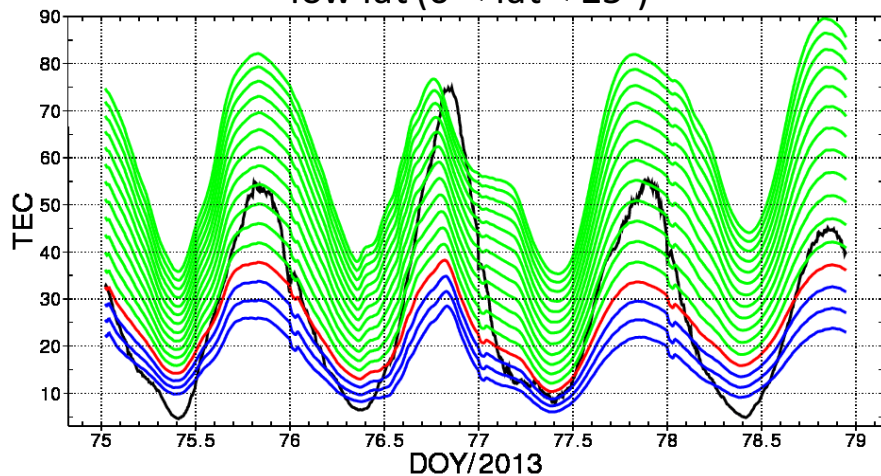
- GPS TEC
- CTIPe TEC with default BF (=1.0)
- CTIPe TEC with decreased BF in decrements of 0.1 ($0.7 \leq \text{BF} < 1.0$)
- CTIPe TEC with increased BF in increments of 0.1 ($1.0 < \text{BF} \leq 1.8$)

	low		middle		high	
BF	min	max	min	max	min	max
TEC_max(pre-storm)-TEC_min(pre-storm)	24	23	8	7	3	3
TEC_max(main phase)-TEC_min(pre-storm)	25	24	8	7	3	3
TEC_max(recovery phase)-TEC_min(pre-storm)	23	23	9	9	4	4

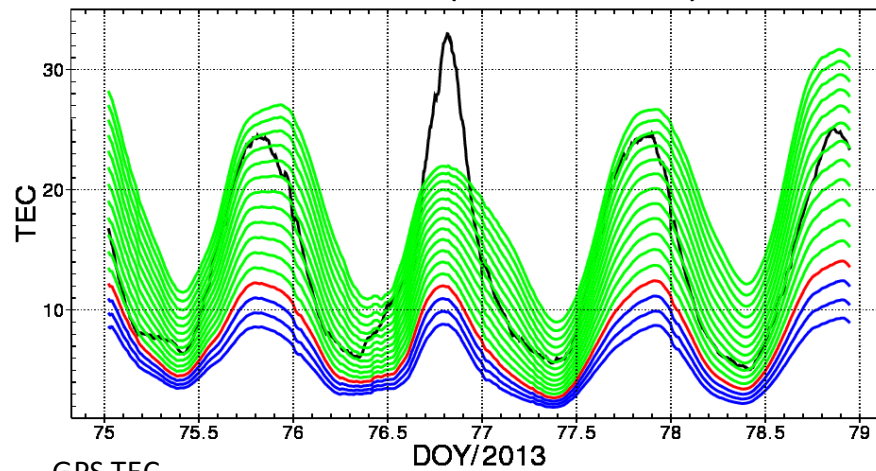
- BF variation has larger impact on TEC in low latitude region than on TEC in higher latitude region.

Sensitivity of TEC to F10.7 (201303)

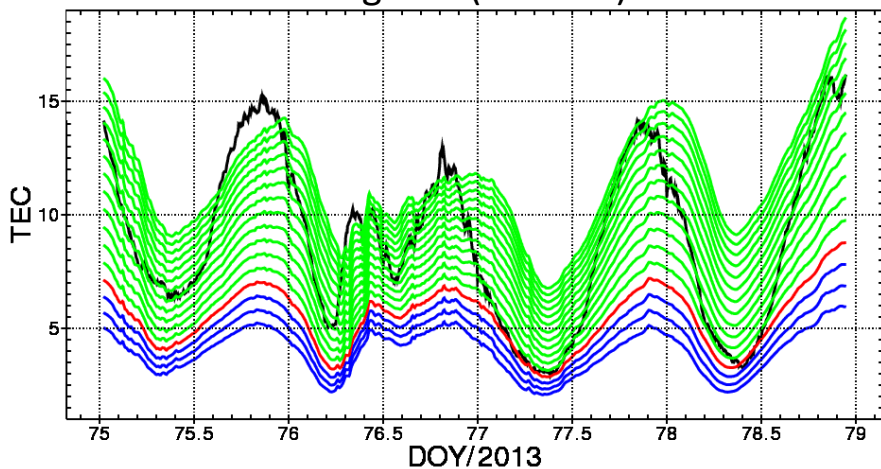
low lat ($0^\circ < \text{lat} < 25^\circ$)



middle lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($50^\circ < \text{lat}$)



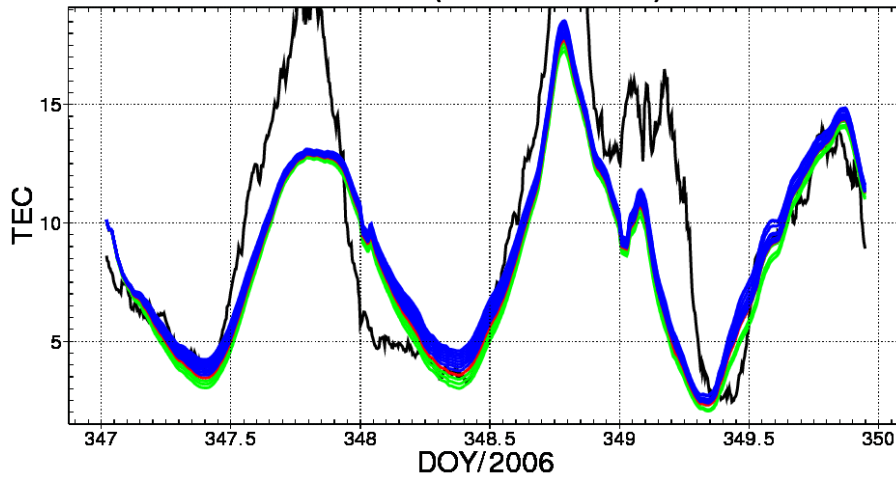
- GPS TEC
- CTIPe TEC with measured F10.7
- CTIPe TEC with increased F10.7 in increments of 10

	F10.7	F10.7A	(F10.7+F10.7A)/2	F10.7 ensemble
03/16	125	112	118	88 ~ 238
03/17	125	113	119	89 ~ 239
03/18	117	113	115	85 ~ 235
03/19	110	114	112	82 ~ 232

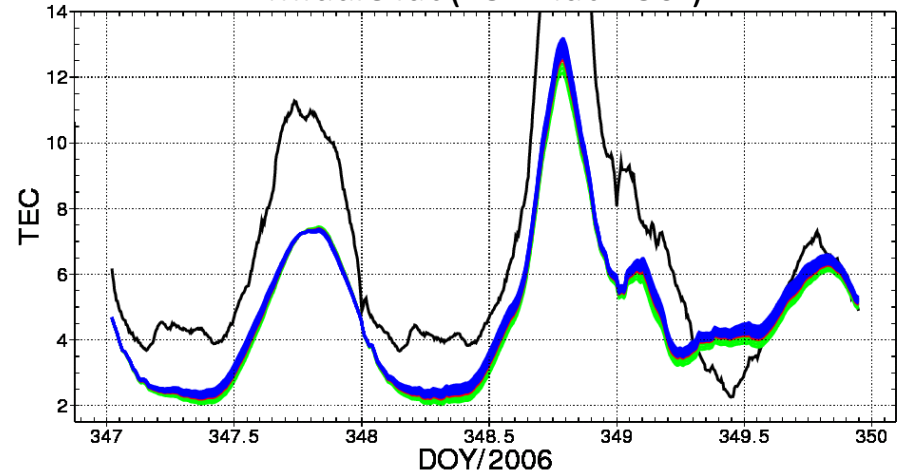
	low		middle		high	
F10.7	min	max	min	max	min	max
TEC_max(pre-storm)-TEC_min(pre-storm)	16	46	6	18	2	7
TEC_max(main phase)-TEC_min(pre-storm)	18	40	5	15	2	5
TEC_max(recovery phase)-TEC_min(pre-storm)	14	54	5.5	20	2.7	7.5

Sensitivity of TEC to Burnside Factor (200612):

low lat ($0^\circ < \text{lat} < 25^\circ$)

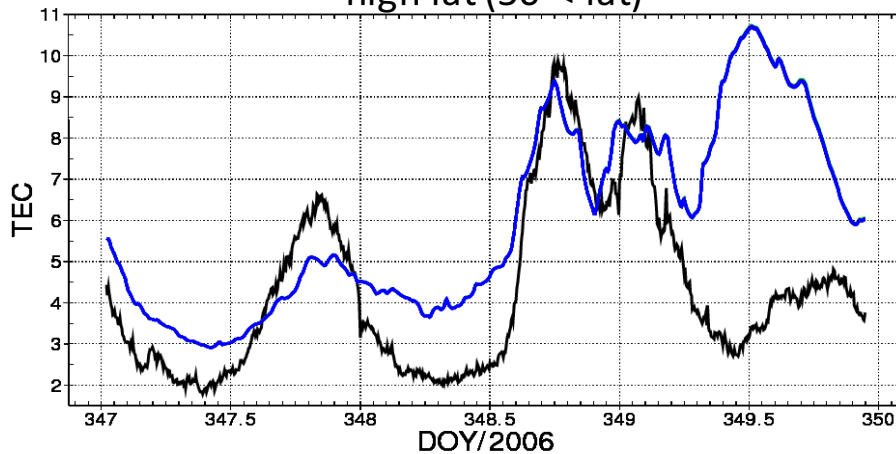


middle lat ($25^\circ < \text{lat} < 50^\circ$)



- GPS TEC
- CTIPe TEC with default BF (=1.0)
- CTIPe TEC with decreased BF in decrements of 0.1 ($0.7 \leq \text{BF} < 1.0$)
- CTIPe TEC with increased BF in increments of 0.1 ($1.0 < \text{BF} \leq 1.8$)

high lat ($50^\circ < \text{lat}$)

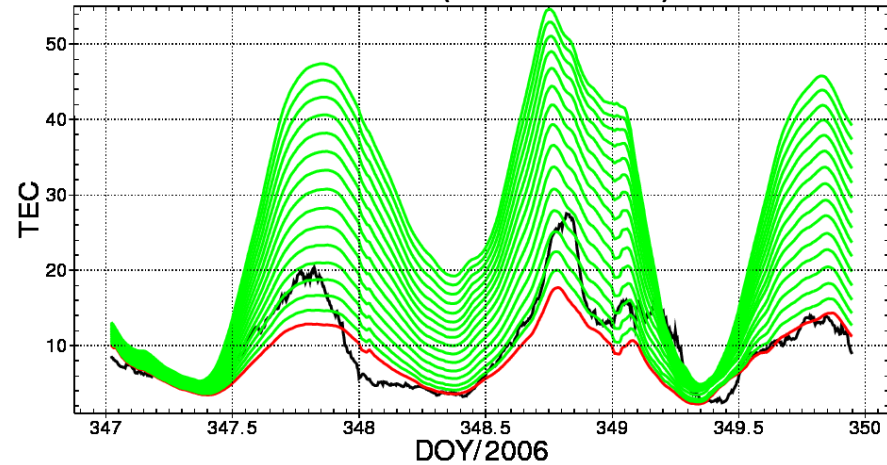


	low		middle		high	
BF	min	max	min	max	min	max
TEC_max(pre-storm)-TEC_min(pre-storm)	10	9	5	5	3	3
TEC_max(main phase)-TEC_min(pre-storm)	14	14	10	11	6	6
TEC_max(recovery phase)-TEC_min(pre-storm)	11	11	4	4	8	8

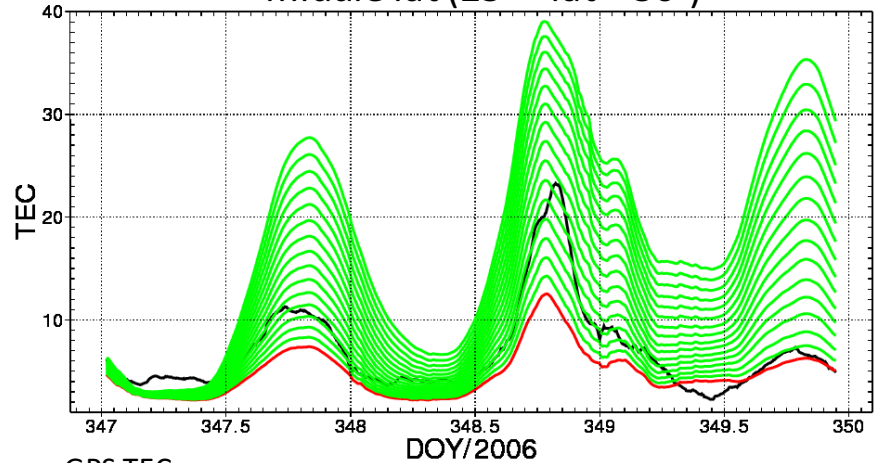
- Effects of BF variation on low and middle latitude TEC during 2013 Mar. storm is larger than those during 2006 Dec. storm.

Sensitivity of TEC to F10.7 (200612):

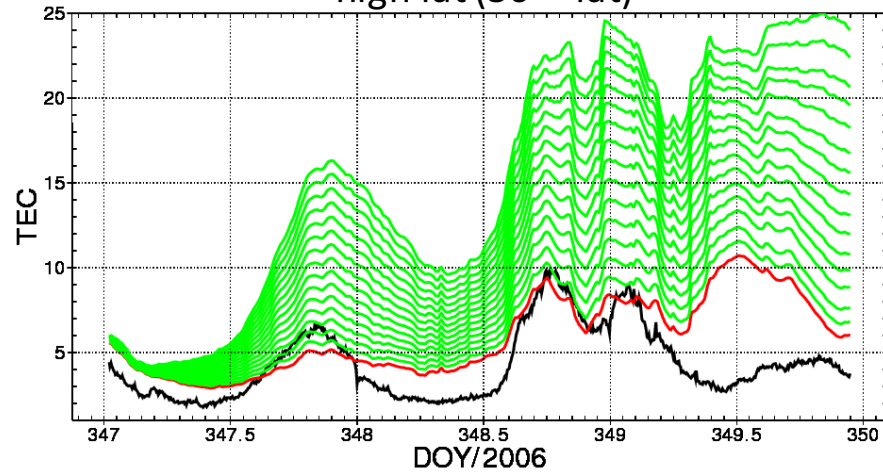
low lat ($0^\circ < \text{lat} < 25^\circ$)



middle lat ($25^\circ < \text{lat} < 50^\circ$)



high lat ($50^\circ < \text{lat}$)



— GPS TEC

— CTIPe TEC with measured F10.7

— CTIPe TEC with increased F10.7 in increments of 10

	F10.7	F10.7A	$(F10.7+F10.7A)/2$	F10.7 ensemble
12/13	91	82	86	86 ~ 236
12/14	91	82	86	86 ~ 236
12/15	84	82	83	83 ~ 233

	low		middle		high	
F10.7	min	max	min	max	min	max
TEC_max(pre-storm)-TEC_min(pre-storm)	9	42	5	25	3	12
TEC_max(main phase)-TEC_min(pre-storm)	14	50	10	36	6	19
TEC_max(recovery phase)-TEC_min(pre-storm)	10	40	4	32	8	20

Summary

- For 2006 Dec. and 2013 Mar. storm events, we evaluated IT model performance of predicting TEC over North America longitude sectors 240°E - 300°E.
 - The IT models used for the study range from empirical model (IRI), physics-based ionosphere model (SAMI3 and USU-IFM), coupled ionosphere-thermosphere physics-based model (CTIPe, TIE-GCM, and GITM) to data assimilation model (USU-GAIM).
 - RMS errors of TEC and shifted TEC ($\text{TEC} - \text{pre-storm TEC}_{\min}$) of the models were calculated.
 - maximum changes; Max_s (max. during storm time) – Max_q (max. during quiet time), Min_s (min. during storm time) – Min_q (min. during quiet time), and $(\text{Max}-\text{Min})_s - (\text{Max}-\text{Min})_q$; were also calculated.
- GPS-TEC (provided by MIT) was used as a ground truth.
 - average error for 200612 event: about 1.8, 1.3, and 0.8 TECU in low, middle, and high latitudes, respectively
 - average error for 201303 event: about 5.6, 3.0, and 1.7 TECU in low, middle, and high latitudes, respectively

- Performance of models depends on

latitudes:

- Data assimilation model, USU-GAIM, shows the best performance in predicting TEC in low and middle latitude regions. However, physics based models show comparable performance to a data assimilation model, USU-GAIM, in high latitude region where GPS-TEC data coverage is relatively poor.

metrics:

- In terms of RMS error, TIE-GCM shows better score than USU-GAIM in high latitudes, while USU-GAIM produces better maximum changes (e.g., $\text{Max}_s - \text{Max}_q$).
- For 2013 Mar. storm, TIE-GCM shows the smallest RMS error of shifted TEC in middle latitudes, while GITM shows the the smallest RMS error of TEC without shifting in high latitudes.

storms:

- CTIPe RMS errors are smaller than GITM for 2006 Dec. storm, while opposite holds true for 2013 Mar. storm.

- Variation of $O^+ - O$ collision frequency ($0.7 < \text{Burnside Factor} < 1.8$)
 - has larger impact on TEC in low latitude region than on TEC in higher latitude region.
 - hardly has impact on maximum changes in TEC (less than 1 TECU) in all three latitude regions.
- Variation of F10.7 (about $80 < \text{F10.7} < 230$)
 - has larger impact on maximum TEC changes (about 30 TECU) in low latitude region than those (about 10 TECU) in higher latitude region.

